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Detecting human impacts on the flora, fauna, and summer monsoon of Pleistocene Australia

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Abstract

All of Australia's largest mammalian vertebrates became extinct 50 to 45 ka (thousand years ago), shortly after human colonization. Between 60 and 40 ka Australian climate was similar to present and not changing rapidly. Consequently, attention has turned toward plausible human mechanisms for the extinction, with proponents for over-hunting, ecosystem change, and introduced disease. To differentiate between these options we utilize isotopic tracers of diet preserved in eggshells of two large, flightless birds to track the status of ecosystems before and after human colonization. δ^{13}C preserved in their eggshells monitor a bird's dietary intake in the weeks to months before egg-laying. More than 500 dated eggshells from central Australia of the Australian emu (*Dromaius novaehollandiae*), an opportunistic, dominantly herbivorous feeder, provide a continuous 140 kyr dietary δ^{13}C reconstruction. More than 350 dated eggshells from the same region of the heavier, extinct, giant bird *Genyornis newtoni* define its dietary intake from 140 ka until its extinction about 50 ka. Additional dietary records for both species were developed from two distant regions. Dromaius eggshell dietary δ^{13}C reveals an unprecedented reduction in the bird's food resources about 50 ka, coeval in all three regions, suggesting conversion at that time of a tree/shrub savannah with occasionally rich grasslands to the modern desert scrub. We speculate that ecosystem collapse across the arid and semi-arid zones is a consequence of systematic burning by early humans. Genyornis diet everywhere is more restricted than in co-existing Dromaius, implying a more specialized feeding strategy. These data suggest that generalist feeders, such as Dromaius, were able to adapt to a changed vegetation regime, whereas more specialized feeders, such as Genyornis, became extinct. The altered vegetation may have also impacted Australian climate. Changes in the strength of climate feedbacks linked to vegetation and soil type (moisture recycling, surface roughness, albedo) may have weakened the penetration of monsoon moisture into the continental interior under the new ecosystem. Climate modeling suggests such a shift may have reduced monsoon rain in the interior by as much as 50%.

1 Introduction

Australia was rifted from Antarctica in the early Tertiary, and since then has drifted slowly northward in isolation on the Austral-Indian plate. Before rifting, marsupials migrated from South America, across Antarctica, and on to the Australian continent, but no placental mammals made the journey. Over the subsequent 50 Myr, the Australian marsupial fauna evolved into unique groups of herbivores and carnivores. The only placental mammals in Australia at the start of the Late Quaternary were bats, and a few small rodents that arrived from SE Asia. As the continent entered the subtropical high-pressure zone in the late Tertiary, and global climate evolved in response to the break up of Gondwanaland, the climate of Australia became more arid, with the ancient Gondwanan plants concentrated in the better-watered eastern seaboard and the southwest, and with newly evolved drought-adapted plants and animals dominating the arid and semi-arid interior. Eggshells of two large, flightless birds adapted to the arid and semi-arid-zones, the extant Australian emu *(Dromaius novaehollandiae)* and the larger and now extinct *Genyornis newtoni*, provide valuable proxy data about environmental conditions over the past 150 kyr.

By the Late Quaternary, the climates of northern Australia and much of the central interior were dominated by the waxing and waning of the Australian Summer Monsoon, that delivered life-giving moisture to the desert interior during global interglaciations, but weakened dramatically during global glaciations, leaving the interior both dry and cold (Magee et al., 2004; Miller et al., 2005b). Even the better-watered coastal fringes witnessed the expansion of grasses at the expense of closed forest ecosystems during global glacial periods (Kershaw, 1991; Kershaw et al., 2003). On millennial timescales, the planetary monsoon system is controlled by the distribution of solar insolation (Milankovitch cycles), sea surface temperatures (SST), and sea level. High SST, high sea level, and peak insolation seasonality are correlated with the penetration of monsoon rainfall deep into continental interiors (Kutzbach et al., 1998; Kutzbach and Guetter, 1986).

2 Waterlevel changes at Lake Eyre: implications for monsoon forcing

The Lake Eyre Basin is a large internal drainage network (1.2×10^6 km^2) fed dominantly by a summer-monsoon rainfall catchment to the northeast (Fig. 1). Lake Eyre (15 m b.s.l) is the terminal playa of the Lake Eyre Basin, and its sedimentary history and paleohydrology constitute a paleorecord of monsoon runoff. In the modern climate regime, Lake Eyre only receives significant fluvial inflows during rare years when an intensified monsoon trough is displaced significantly to the south, or one or more discrete monsoon depressions, characterized by intense convection and heavy rainfall, reach into the Lake Eyre Basin. Although Lake Eyre is an ephemeral playa in the modern regime, beaches above the modern playa, deep-water lacustrine sediments found in boreholes and cliffed exposures, and fluvial aggradation in inflowing streams define intervals of perennial lacustrine conditions during the Middle and Late Quaternary. Under drier conditions, playa deepening occurs as evaporation lowers the saline water table and salt-disrupted sediment is deflated to downwind transverse dunes or lunettes, or is removed from the basin as dust. Deflation of lake sediment results in the incision of inflowing streams as they adjust to the lowered base level.

Magee et al. (2004) use these features and multiple dating techniques to derive a nearly continuous record of waterlevel changes in Lake Eyre for the past 150 kyr (Fig. 2). Greatest effective aridity in that period occurred in MIS (marine oxygen isotope stage) 6, when an interval of depressed groundwater allowed deflation to lower the playa surface 4.3 m below its current level (Magee et al., 1995; Magee and Miller, 1998). This arid event was followed abruptly by the wettest phase of the past 150 kyr, with a perennial lake stabilizing at 10 m a.s.l, nearly 25 m above the modern playa, during the last interglaciation (ca. 130 to 120 ka). Coeval fossil assemblages indicate diverse and abundant aquatic and terrestrial ecosystems, including now-extinct megafauna, lived in and around Lake Eyre (Tedford and Wells, 1990). Records signifying an enhanced Australian monsoon during the last interglaciation come from other Lake Eyre catchment fluvial sites (Croke et al., 1996; Nanson et al., 1988) and other monsoon-fed lakes

of northern Australia (Bowler et al., 1998, 2001).

Following the peak waterlevel of MIS 5e, Lake Eyre shallowed and briefly dried at least once, but no evidence is seen of deflation or pedogenesis, before refilling again to 5 m a.s.l. between 100 and 75 ka. Fluctuations in lake level and salinity suggest decreasing regularity of inflow and gradual diminution of the monsoon toward the end of this wet phase. Lake sediments were pedogenically modified and eventually truncated by deflation when the lake dried at 75 to 70 ka and disrupted gypsiferous playa sediments were transported downwind. Incision of tributary rivers into fluvial and lacustrine sediments graded to the earlier high-water phase extends almost to the modern level, documenting a transition to significant aridity and deflation. Lacustrine conditions returned 65 to 60 ka, depositing lake sediment and a prominent beach at about 3 m b.s.l.; coeval fluvial aggradation and vertical accretion of overbank muds occurred. This phase represents the last deep-water perennial lake and the last interval of at least moderately effective monsoon precipitation in the basin. Subsequent eolian deflation excavated the modern Lake Eyre playa, reflecting a major change in hydrological conditions from high to low water tables, rather than extreme aridity. The youngest articulated marsupial megafaunal remains found around Lake Eyre occur in lunette sediments deposited by this event at about 55 to 45 ka (J. W. Magee and others, unpub. OSL & ESR dates), similar to the youngest dated Genyornis (Miller et al., 1999).

After a prolonged period of drought and irregular minor playa deflation from 35 to 14 ka, the onset of low-level, perennial, lacustrine conditions occurred by 12 ka (Gillespie et al., 1991). The onset of wetter conditions in Lake Eyre closely follows monsoon regeneration in northwestern Australia at 14 ka (Wyrwoll and Miller, 2001). Reduced inflow to Lake Eyre after 4 to 3 ka established the modern ephemerally flooded playa regime. The absence of early Holocene beaches suggests that the lake was below the highest floods of the modern ephemeral regime (6.7 to 8.8 m. b.s.l.) (Dulhunty, 1975). The mode change to less frequent but more extreme events may reflect a change in the character of ENSO in the middle Holocene, as suggested by previous studies (Rodbell et al., 1999).

Two intriguing conclusions have been derived from the 150 kyr waterlevel curve for Lake Eyre (Fig. 2). The pacing of the Australian Monsoon through the Late Quaternary follows precessional Milankovitch frequencies, within the uncertainties of the dating. The Lake Eyre highstands during MIS 5e and early in MIS 1 occurred during Northern Hemisphere winter insolation minima, that results in enhanced outflow from the Siberian high-pressure cell (Magee et al., 2004). In contrast, the Australian continent experienced a summer insolation minima during the highstands. These relations suggest primary Northern, rather than Southern Hemisphere insolation forcing of the Australian Monsoon on millennial timescales. A second conclusion regards the waterlevel in the Holocene, which is significantly lower than 65–60 ka, even though primary monsoon forcings 65–60 ka (insolation, SST, sea level) were weaker than in the Holocene. The lack of a Holocene highstand in Lake Eyre contrasts with substantial reinvigoration of the planetary monsoon in the early Holocene outside Australia (Carmouze and Lemoalle, 1983; Hoelzmann et al., 2000; Liu and Ding, 1998; Rousseau and Wu, 2000; Wasson, 1995; Williams et al., 2000) and coeval reactivation of the monsoon along the northern Australian fringe at this time (Nanson et al., 1991; Nott and Price, 1994). Climate modeling of the planetary monsoons during the Holocene (Liu et al., 2003; Marshall and Lynch, 2006) also simulates a stronger Australian Monsoon during the early Holocene than at present, consistent with Northern Hemisphere winter insolation forcing, rather than direct insolation forcing over the Australian continent, unlike the monsoons over southern Africa and South America. The failure of the Holocene monsoon evidenced by the Lake Eyre waterlevel curve was interpreted by Magee et al. (2004) to suggest that there must have been a significant boundary condition change over Australia sometime between 60 ka and the early Holocene.

3 Large-scale changes in Australia after 60 ka

Australia suffered a major loss of its large- and medium-sized land mammals in the Late Quaternary. All marsupials >100 kg (19 species) and 22 of 38 species between 10 and

100 kg became extinct (Flannery, 1990), along with three large reptiles and the ostrich-sized *Genyornis newtoni* (Murray and Vickers-Rich, 2004); two other large flightless birds, the emu *(Dromaius novaehollandiae)* and the cassowary *(Casuarius casuarius)* survived. Dwarfing and range restriction occurred in many other species (Flannery, 1990). Collectively, the lost species are often referred to as the Australian megafauna, although most are of modest body mass. For more than a century the cause of this exceptional extinction has been debated without a clear consensus, largely due to the difficulty in dating faunal remains close to the limit of radiocarbon dating (Baynes, 1999). Debate about the cause of megafaunal extinction initially focused on climate change (Tate, 1879) or human predation (Owen, 1877), but more recently has included indirect consequences of human activity, particularly ecosystem change resulting from burning practices (Jones, 1969, 1973; Merrilees, 1968). Resolving the debate requires secure dates on the extinction event(s), on the arrival of humans in Australia, and on major climate and environmental changes.

Recent advances in geochronology indicate that humans had colonized Australia widely by 50 ka (Bowler et al., 2003; Gillespie et al., 2006; Roberts et al., 1998, 1990; Turney et al., 2001a). The application of new dating tools and refinements in older methods now place the extinction of the Australian megafauna to between 50 and 45 ka (Miller et al., 1999; Roberts et al., 2001). The largest datasets of direct dates on megafaunal remains are on the eggshells of Genyornis. These include datasets from Lake Eyre, Lake Frome, Port Augusta and the Darling-Murray lakes (Fig. 1). More than 1000 dated Genyornis eggshells from around Lake Eyre show the bird's continuous presence from at least 140 ka until about 50 ka, and its subsequent complete absence in the region (Fig. 3). Eggshells of Dromaius, the Australian emu, which breeds in the same sand hills favored by Genyornis for breeding sites, are continuously present throughout the last 140 ka (Fig. 3). Smaller time series for other regions of Australia have the same date for Genyornis extinction, 50±5 ka (Fig. 4). Lake Eyre is representative of the arid core of the continent, whereas the Darling-Murray lakes represent some of the best-watered sites in the interior, at the juncture of the monsoon-fed Darling and

winter-westerly-fed Murray rivers. If climate were the primary driver of extinction, we would expect to see a retraction of the megafauna to the most favorable watering sites, where extinction dates would be later than in the arid core. The lack of any difference in the timing of extinction of Genyornis across a wide climate space suggests climate is not a likely cause of Genyornis extinction.

The absence of significant climate change between 60 and 40 ka (Hesse et al., 2004; Kershaw et al., 2003; Magee et al., 2004) has focused attention on plausible human mechanisms for megafaunal extinction. Given Australia's long isolation from any large placental mammals, and the capability of humans to modify landscapes even with relatively low-technology tool-kits, it seems appropriate to ask whether human colonization of the continent might have resulted in unprecedented changes to the flora and/or fauna of Australia. In addition to ecosystem modification (Jones, 1969; Merrilees, 1968; Miller et al., 1999), over-hunting (Flannery, 1994) and introduced diseases (MacPhee and Marx, 1997) have been suggested as plausible human mechanisms. To differentiate between these and other potential explanations we have sought to reconstruct the diets of Genyornis and Dromaius before and after human colonization.

4 Paleodietary reconstructions

Of the 60 Australian taxa known to have gone extinct in the Late Pleistocene, both size and feeding strategy have some predictive potential (Johnson and Prideaux, 2004). Most of the extinct taxa were large browsers, whereas large grazing forms, such as red and gray kangaroos, as well as many smaller browsers were less impacted. The selective loss of large browse-dependent taxa suggests ecosystem change may have been important. Fire can be an effective agent of ecosystem change. Humans have had controlled use of fire since the Middle Quaternary. They burn landscapes for many purposes, from clearing passageways and hunting along the fire-front, to signaling distant bands and promoting growth of preferred plants. Tantalizing inferential evidence for vegetation change and burning by humans about 50 ka is recorded by pollen changes

in terrestrial (Kershaw, 1986; Turney et al., 2001b) and marine (Kershaw et al., 2003) sediment cores, but pollen is rarely preserved across the arid and semi-arid zones, hampering similar investigations across most of the country. To circumvent the lack of pollen, we rely instead on isotopic tracers of diet preserved in biominerals (Johnson et al., 1998; Koch et al., 1994) to track changes in ecosystems before and after human colonization of Australia.

Almost counterintuitively, the most abundant megafaunal remains found across arid and semi-arid Australia are eggshells of the two large, flightless birds, Genyornis and Dromaius. Bird eggshells are a calcite biomineral of exceptional preservation potential. They contain 3% organic matter, most of which is sequestered within the calcite crystals of the eggshell where it is stable in the geological environment for millions of years. We use two independent measures of the birds' dietary $\delta^{13}C$; the $\delta^{13}C$ in the calcite minerals that make up the eggshell structure ($\delta^{13}C_{carb}$), and the $\delta^{13}C$ in the organic matrix that birds place within the calcite minerals to give the eggshell resiliency ($\delta^{13}C_{org}$). Carbon used by a bird in making its eggshell (organic and carbonate carbon) comes from the food it has eaten, offset by systematic biochemical fractionation factors (Johnson et al., 1998). Calcite carbon is derived from dissolved bicarbonate in the bloodstream, which has a relatively rapid cycle time, reflecting food sources in days to weeks before egg-laying, whereas eggshell organic carbon is derived from protein reserves that may integrate dietary intake over several months.

Our 140 000 year dietary reconstruction for Dromaius from Lake Eyre is based on $\delta^{13}C_{org}$(n=180) and $\delta^{13}C_{carb}$(n=343) values in individually dated eggshells (Miller et al., 2005a). Between 50 and 45 ka, mean dietary $\delta^{13}C$ decreased by at least 3.3% (95% confidence level), accompanied by an even larger decrease in dietary variance, from 14.4 to 3.5% (Fig. 5). Prior to 50 ka, Dromaius ate a wide range of food sources, ranging from a nearly pure C4 diet to a nearly pure C3 diet, with almost any combination of intermediate feeding strategies. This $\delta^{13}C$ distribution is consistent with an opportunistic feeder that lived in an environment with high inter-annual moisture variability, suggesting abundant, nutritious C4 grasslands in wet years, and a dominance

of C3 shrubs and trees in drier years. After 45 ka, Dromaius utilized a restricted range of food sources, dominated by C3 plants. The magnitude and irreversible signature of this dietary change suggests ecosystem collapse around Lake Eyre between 50 and 45 ka. We find synchronous shifts in δ^{13}C of Dromaius eggshells collected from two distant regions, Port Augusta and the Darling-Murray Lakes (Fig. 6), suggesting the ecosystem change was not restricted to the core arid zone around Lake Eyre, but characterized a large portion of the arid and semi-arid zones.

Dietary reconstructions for the extinct megafaunal bird, Genyornis, indicate a more specialized feeding strategy than for coexisting Dromaius; Genyornis exhibits only 40% of the isotopic variance observed in contemporary Dromaius around Lake Eyre. Genyornis diet from all three regions (Fig. 6) always includes some C4 dietary sources, unlike Dromaius, which tolerates a pure C3 diet. We conclude that Genyornis was a more specialized feeder than Dromaius, targeting a specific set of food resources, and that these resources must have remained available through the range of climates between 140 and 50 ka.

Evidence for ecosystem change is recorded in mammals as well as avian taxa. Wombats are extant burrowing grazing marsupials that lived in the same sandhills favored by Genyornis and Dromaius as nesting sites. Preservation of their skulls is favored by sometimes dying in their burrows. Wombat skulls are occasionally found in recent sandhill exposures, where they can be dated by their association with dated eggshells. Wombats primarily eat grasses, with no known strong preference for C3 or C4 types. Consequently, changes in δ^{13}C along the growth lines of their teeth reflect changing abundances of C3 and C4 grasses in their local environments (Fraser, 2006). Preliminary data on Wombat diets derived from the δ^{13}C in their tooth enamel show the same patterns observed in Dromaius eggshells (Fig. 6). The greater proportion of C4 grass in Wombat diets prior to 50 ka than after 45 ka, lends strong support to our interpretation of ecosystem change derived from the Dromaius dietary reconstructions.

Our eggshell and wombat tooth derived δ^{13}C data provide firm evidence for an abrupt ecological shift around the time of human colonization and megafaunal extinc-

tion in Australia, between 50 and 45 ka. Climate forcing of the observed vegetation change is unlikely, given that earlier dramatic climate shifts did not result in such a large biotic response, and that climate change between 60 and 40 ka was not large, consistent, or sustained. During this interval the Darling-Murray region experienced somewhat greater effective moisture, whereas modest drying occurred around Lake Eyre (Bowler et al., 2003; Hesse et al., 2004; Magee et al., 2004). To further test if climate could be a dominant control on the diet of the two birds, Miller et al. (2005a) subdivided the time series in Fig. 5 into 15 kyr intervals; these include the contrasting climates of the Holocene, the last glacial maximum, and the last interglaciation. The mean and variance of each interval are not statistically different from the mean and variance of their larger groupings (>50 and <45 ka), suggesting that climate is not the dominant control on dietary $\delta^{13}C$.

We contend that a changed fire regime is a plausible mechanism for the observed ecosystem reorganization. Although Australia has a long history of burning by natural ignition, early human colonizers may have altered the timing and frequency of biomass burning. We hypothesize that systematic burning practiced by the earliest human colonizers may have converted a drought-adapted mosaic of trees and shrubs intermixed with palatable nutrient-rich grasslands to the modern fire-adapted grasslands and desert scrub. Nutrient-poor soils (Barrett, 2002) would have facilitated the replacement of nutritious C4 grasses by spinifex, a fire-promoting C4 grass that is well adapted to low soil nutrients. A range of C3 plants may have been lost at the same time, but the isotopic dietary proxy lacks sensitivity to such a loss.

We emphasize that the dietary records (Figs. 5, 6) reflect what the birds actually ate, and are not necessarily representative of the vegetation growing in these regions. The dominance of C3 food in Dromaius diet after 45 ka appears to be the opposite of what would be predicted if an increase in fires, as we suggest, is the cause of ecosystem change. Greater burning should promote the expansion of C4 grasses at the expense of other plants. In fact, this is what happened. It is just that the C4 grasses are dominated by spinifex and canegrass, neither of which is palatable, hence they do

not contribute substantially to Dromaius' diet. Analyses of modern (1970–2000 AD) *Dromaius* eggshells from the Lake Eyre region show virtually no C4 elements in the birds' diets even though canegrass (C4) is a dominant vegetation type (Johnson et al., 2005).

5 Human-biosphere-climate interactions

The summer monsoon is one of the most energetic elements of the global climate system. On Quaternary timescales, the intensity of the planetary monsoon system has varied in response to changes in the distribution of solar insolation, and glacial-interglacial cycles of sea level and SST (Kutzbach et al., 1998). The Australian Monsoon, a modest peripheral component of the Asian Monsoon, dominates the moisture balance across northern Australia. Present summer precipitation exceeds 1000 mm along the north coast, but diminishes rapidly inland to less than 300 mm within a few hundred km of the coast; only infrequently do heavy monsoon rains penetrate deep into the continental interior. Monsoon rainfall across Australia has systematically deviated from the modern regime during the Quaternary. Several proxy records as well as climate models discussed above support the dominant control of Northern Hemisphere insolation on the intensity of monsoon rainfall over Australia on millennial timescales (Magee et al., 2004; Miller et al., 2005a). Based on these studies, strong monsoon flow should have delivered sufficient moisture into the Australian interior during the early Holocene to create a permanent deep-water lake in Lake Eyre. The absence of such a lake is an enigma (Magee et al., 2004).

In addition to large-scale forcing of the planetary monsoon system, local boundary conditions also impact the distribution of monsoon rainfall. Vegetation and soil influence the penetration of moisture into tropical regions through the recycling of water, changes in surface roughness, changed albedo and other phenomena (Charney, 1975; Lapenis and Shabalova, 1994). On Quaternary timescales, altered boundary conditions linked to vegetation and soil type are thought to amplify climate change across other mon-

soon regions (Brostrøm et al., 1998; Kutzbach et al., 1996; Zeng et al., 1999). We hypothesize that the dramatic vegetation change observed in our isotopic dietary data may have played a role in the failure of the Holocene monsoon observed at Lake Eyre.

To test this hypothesis, we used a global climate model to evaluate the sensitivity of monsoon precipitation to the state of vegetation and soil across Australia (Miller et al., 2005b). Recognizing that large-scale forcing of the planetary monsoon system is not likely to be altered by human activity, we chose a 10 ka timeslice as our control, when other climate models (Liu et al., 2003; Marshall and Lynch, 2006) as well as paleodata indicate that summer (DJF) precipitation across monsoonal Australia was above present. Intervals when regional airflow across northern Australia is from the north and the monsoon trough is close to the continent are the optimal times for local boundary conditions to influence the penetration of monsoon rainfall into the interior of Australia. We compared the differences in simulated monsoonal precipitation over Australia between a 10 ka control run, and 10 ka simulations when Australia is prescribed as "forested" and when it is prescribed as "desert". Significant increases in DJF precipitation occur across northern Australia when the continent is forested, whereas smaller, but significant decreases in precipitation relative to the 10 ka control are simulated when Australia is prescribed as desert (Fig. 7). DJF precipitation is more than 3 mm day^{-1} greater across northern Australia when the continent is forested than when it is desertified, diminishing to 0.5 mm day^{-1} by mid continent. Over the northern Lake Eyre catchment, this amounts to an effective doubling of the average annual precipitation. Because the global climate model was a relatively low-resolution model, and the simulations were designed as sensitivity tests rather than simulations of specific intervals in the past, these results cannot be used as specific predictors of past monsoon rainfall amounts. However, they do confirm that vegetation and soil characteristics across monsoonal Australia play a significant role in determining the penetration of monsoon moisture in the interior.

6 Summary and conclusions

The geologic evidence from Lake Eyre indicates that a weak but regular monsoon operated during the early Holocene, whereas the late Holocene is characterized by reduced monsoonal precipitation (Magee et al., 2004), consistent with Northern Hemisphere forcing of the Australian Summer Monsoon. At no time in the Holocene did the Lake Eyre Basin receive sufficient monsoon rain to establish a permanent deep-water lake in Lake Eyre as existed for long periods between 130 and 75 ka, despite similar forcing. The failure of the Holocene monsoon is even more pronounced by the contrast between a permanent deep-water lake in Lake Eyre 65 to 60 ka ago, even though insolation, sea level and SST were less favorable for strong monsoonal flow than at any time in the Holocene. The failure of the Holocene monsoon, despite reinvigoration of the rest of the planetary monsoon system in the early Holocene, has been an enigma. Dietary reconstructions for Dromaius and Genyornis, coupled with our climate modeling sensitivity tests, offers a plausible explanation for this enigma. The dramatic reduction in dietary intake exhibited by our isotopic data from Dromaius eggshells collected from a wide range of sites across arid and semi-arid Australia indicates a rapid, dramatic and irreversible reduction in the food resources available to this generalist feeder between about 50 and 45 ka. A smaller time series of dietary reconstructions for the wombat, a marsupial grazer, show a similar retraction of dietary resources at the same time. Together these datasets suggest a dramatic upheaval at the base of the food chain, with the permanent conversion of a tree/shrub savannah landscape, with common years of exceptionally rich grasslands prior to 50 ka, to the modern impoverished desert scrub by 45 ka, dominated by unpalatable fire-promoting spinifex and canegrass. Dromaius, a generalist feeder, was able to adjust its feeding strategies to the changed ecosystem, whereas Genyornis, and presumably other specialized feeders, were not.

The observed ecosystem change may have had strong feedbacks on the climate system, particularly the penetration of monsoon moisture into the interior of Australia. Although our climate modeling work was necessarily at a relatively low resolution, it

suggests that when forcing for the Australian Summer Monsoon is at its strongest (high sea levels, warm oceans, and strong high pressure over Asia in boreal winter), the status of vegetation and soil type across Australia may determine how deeply monsoon rains will penetrate into the continental interior. The reduction in surface roughness, changed albedo, reduced recycling of rainfall by evapotranspiration, and more rapid runoff, all of which would accompany a transition from the a treed-savannah to the modern desert scrubland, may have resulted in a significant weakening of monsoon rain over the Lake Eyre Basin, and even as far south as Port Augusta and the Darling-Murray Lakes. Much higher resolution climate modeling is currently underway to better test this conclusion.

Although our datasets document an unprecedented ecosystem change between about 50 and 45 ka, they offer little direct evidence for what caused the observed changes. We have speculated that systematic burning by the earliest human colonizers could have changed the fire regime sufficiently across the arid and semi-arid zones, where nutrients are the lowest of any continental region (Barrett, 2002), to disrupt the pre-existing landscape (Johnson et al., 1999; Miller et al., 1999, 2005a, b). Our results, coupled with circumstantial evidence for extensive burning by early human colonizers (Kershaw, 1986; Kershaw et al., 2003; Turney et al., 2001b), suggest that firing of landscapes may have rapidly converted a drought-adapted mosaic of trees, shrubs, and rich grassland to the modern fire-adapted desert scrub; animals that could adapt, survived, those that could not, became extinct. Continued burning, at least until European settlement, would have maintained the changed ecosystem. Altered biosphere-atmosphere feedbacks under the changed ecosystem may have weakened the penetration of monsoon moisture into central Australia, leading to long-term desertification of the continent.

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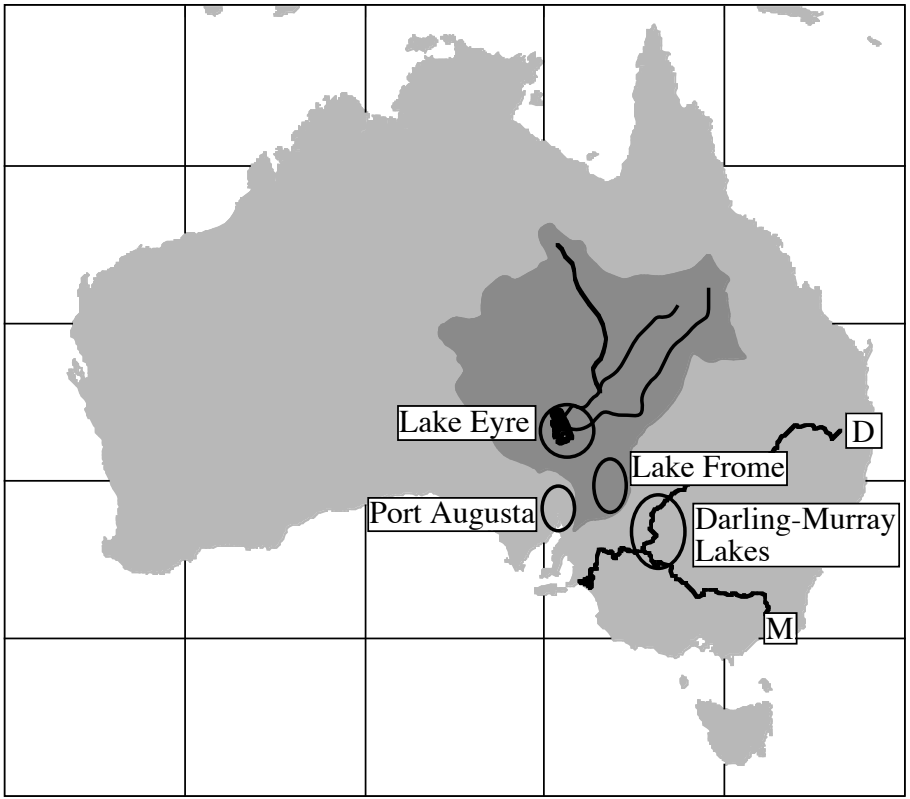

Fig. 1. Map of Australia showing the Lake Eyre Basin (dark shading) with Lake Eyre and its major fluvial systems, and generalized areas from which eggshell have been collected around Lake Eyre Port Augusta, Lake Frome, and the Darling-Murray Lakes. The Darling (D) and Murray (M) rivers are indicated.

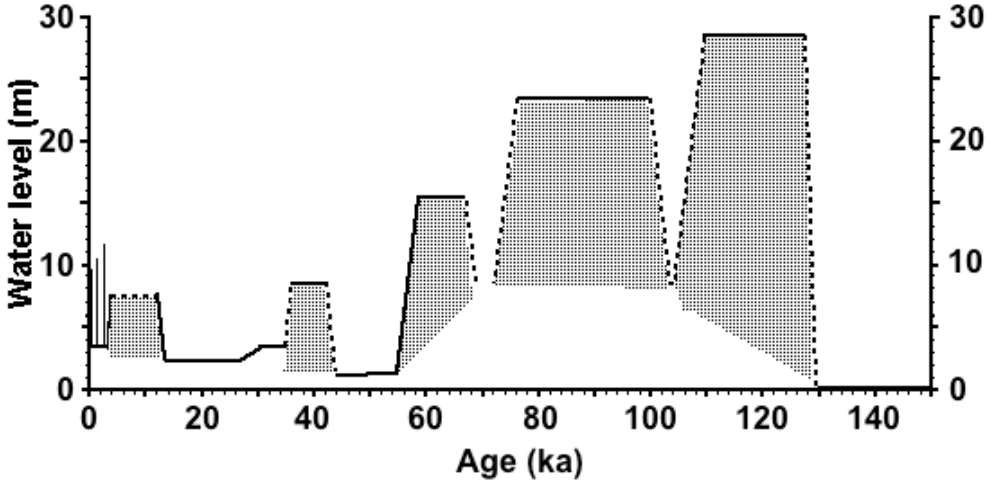

Fig. 2. Lake Eyre waterlevel curve for the past 150 ka (modified from Magee et al., 2004). Elevations are meters above the deepest basin if all current Quaternary sediment were removed. The lake floor was last excavated to this level during the extreme aridity of MIS 6.

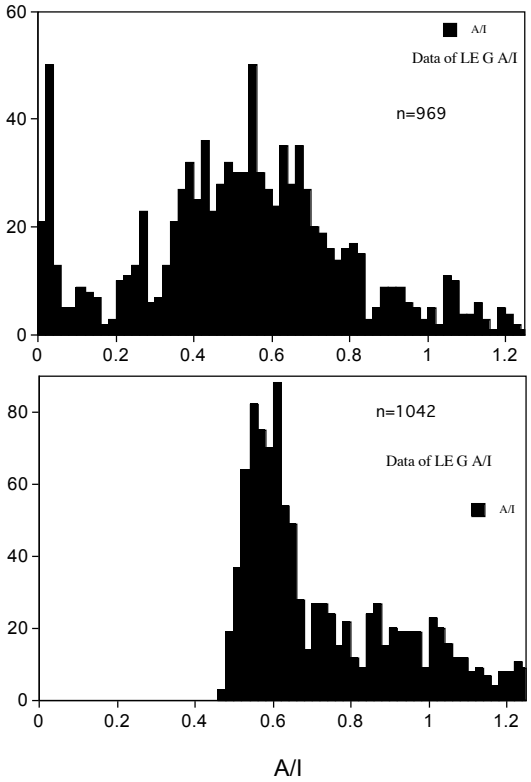

Fig. 3. Frequency histograms showing the extent of amino acid racemization (A/I) in eggshells of Genyornis and Dromaius from Lake Eyre region over the past 150 ka, showing the continuous presence of the later and the complete disappearance of the former about 50 ka. The number of samples in both datasets (*n*) is considerably expanded from the data available to Miller et al. (1999), but the conclusions remain the same.

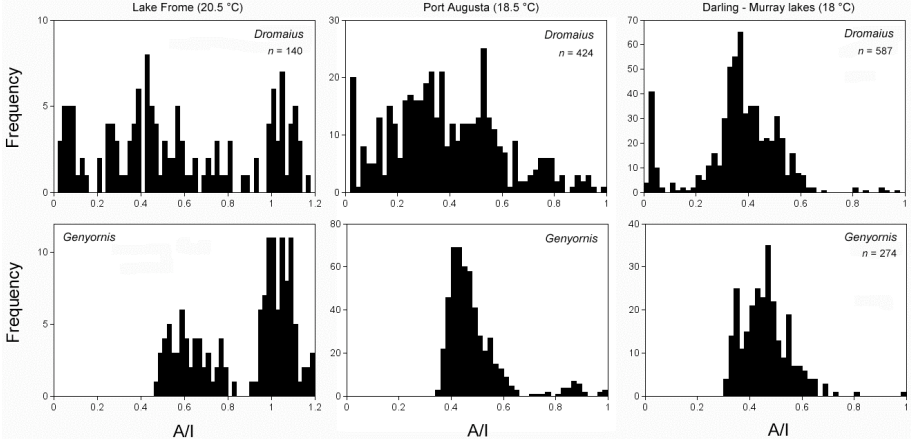

Fig. 4. Frequency histograms of A/I for Genyornis and Dromaius from collections made around Lake Frome, Port Augusta, and the Daring-Murray lakes, with dates on the youngest samples derived from calibrated A/I (Miller et al., 2005a) adjusted for the current temperature differential between each region and Lake Eyre using equations in Miller et al. (2000). The actual A/I for Genyornis at extinction becomes increasingly lower at cooler sites because of the temperature-dependence of racemization rate. Earlier versions of these graphs with fewer analyses are in Miller et al. (1999).

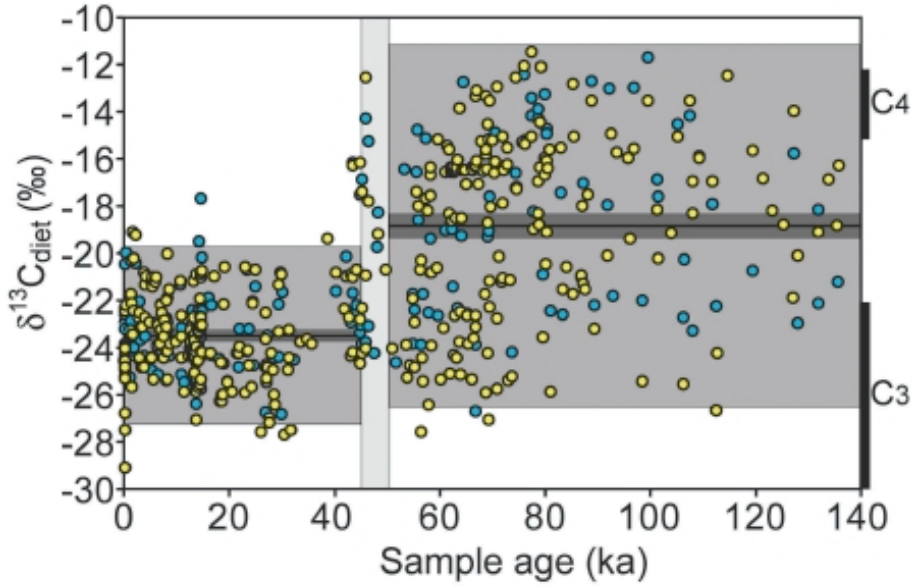

Fig. 5. 140 kyr dietary δ^{13}C record for *Dromaius* from around Lake Eyre, showing the dramatic change in dietary resources that occurred between 50 and 45 ka. Each sample has been independently dated. Light gray shading represents $\pm 1\sigma$s darker gray represents the standard error about the mean, and black line represents the mean δ^{13}C. Range of δ^{13}C in modern vegetation around Lake Eyre is shown by bars on the right side of the graph. Modified from Miller et al., 2005a)

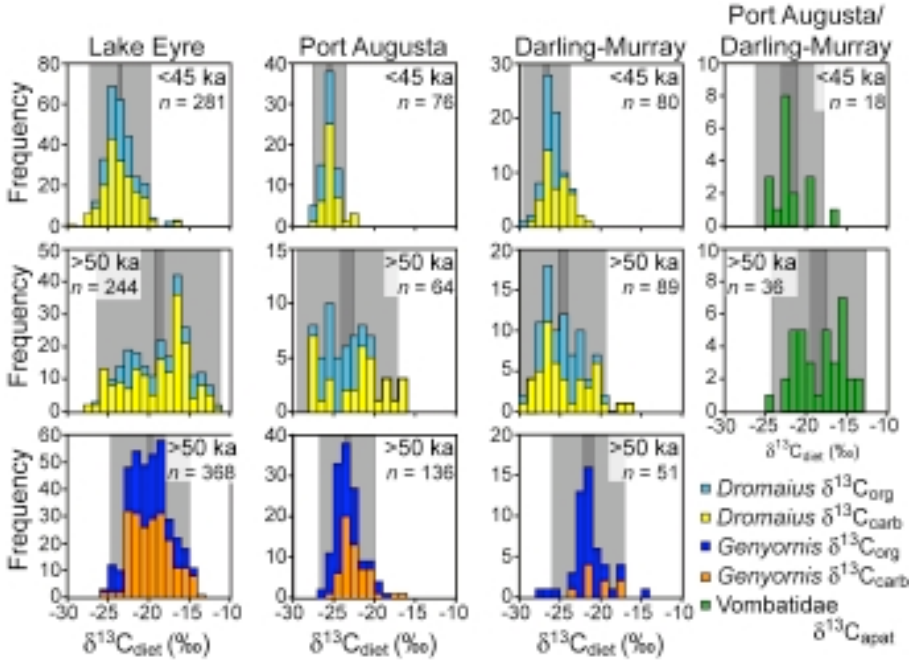

Fig. 6. Histograms of dietary $\delta^{13}C$ for Dromaius and Genyornis eggshell and Wombat tooth enamel from Lake Eyre, Port Augusta and the Darling-Murray lakes contrasting the diets of animals that lived before 50 ka with those living after 45 ka. From Miller et al. (2005a).

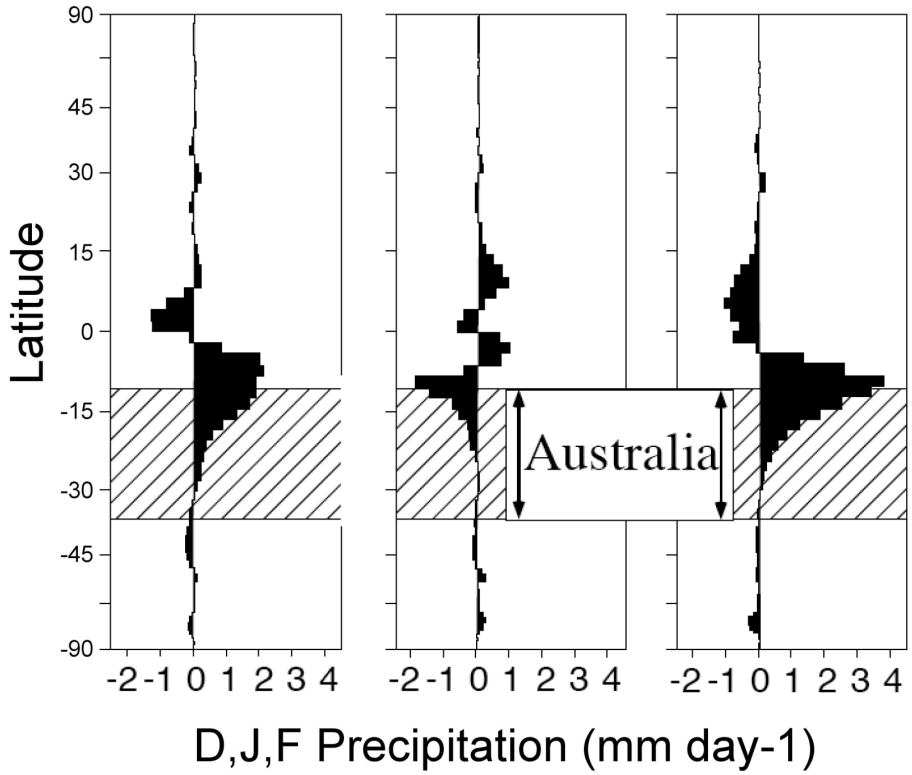

Fig. 7. Differences in simulated monsoon season (December, January, February [DJF]) precipitation along a N-S latitudinal window that encompasses Australia (125–145° E) between a 10 ka control run (interactive vegetation) and a 10 ka simulation with Australia prescribed as forested with loamy soils panel **(a)**, and covered by desert vegetation with sandy soils panel **(b)**. The difference in precipitation between a vegetated and desertified Australia (panel a minus panel b) is shown in panel **(c)**. Details of the climate modeling are presented in Miller et al. (2005b).